

Testing the local-void alternative to dark energy using galaxy pairs

F. Y. Wang^{*} and Z. G. Dai[†]

School of Astronomy and Space Science, Nanjing University, Nanjing 210093, China

Key laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, Nanjing 210093, China

17 April 2013

ABSTRACT

The possibility that we live in a special place in the universe, close to the center of a large, radially inhomogeneous void, has attracted attention recently as an alternative to dark energy or modified gravity to explain the accelerating universe. We show that the distribution of orientations of galaxy pairs can be used to test the Copernican principle that we are not in a central or special region of Universe. The popular void models can not fit both the latest type Ia supernova, cosmic microwave background data and the distribution of orientations of galaxy pairs simultaneously. Our results rule out the void models at the 4σ confidence level as the origin of cosmic acceleration and favor the Copernican principle.

Key words: cosmology: theory - dark energy

1 INTRODUCTION

The standard model of cosmology based on the cosmological principle (homogeneity, isotropy, validity of General Relativity) which contains about 23% dark matter, 4% ordinary matter and 73% dark energy driving the acceleration of a flat universe has been established. Many astronomical observations support this standard picture, including type Ia supernovae (SNe Ia) (Riess et al. 1998; Perlmutter et al. 1999), cosmic microwave background (CMB) (Komatsu et al. 2011; Sherwin et al. 2011), baryon acoustic oscillations (BAO) (Eisenstein et al. 2005) and gamma-ray bursts (Dai et al. 2004; Wang et al. 2007; 2011).

In the meanwhile, inhomogeneous Lemaître-Tolman-Bondi (LTB) (Lemaître 1933; Tolman 1934; Bondi 1947) universe could also induce an apparent dimming of the light of distant supernovae. The idea is to drop the dark energy and the Copernican principle, and instead suppose that we are near the center of a large, nonlinearly underdense, nearly spherical void surrounded by a flat, matter dominated Einstein-de Sitter (EdS) spacetime. Because the observer must be at the center of void, so the LTB models violate the Copernican principle. Because of the observed isotropy of the CMB, the observer must be located very close to the center of the void (Alnes & Amarzguoui 2006). It was demonstrated LTB models can fit the SNe Ia data, as well as the BAO data and the CMB data (Garcia-Bellido & Haugboelle 2008). Some tests have actually been proposed: the

Goodman-Caldwell-Stebbins test, which looks at the CMB inside our past lightcone (Goodman 1995; Caldwell & Stebbins 2008), the curvature test, which is based on the tight relation between curvature and expansion history in a Friedmann spacetime (Clarkson et al. 2008), and the radial and transverse BAO scale (Zibin et al. 2008; Garcia-Bellido & Haugboelle 2009). However, based on these tests, void models have not yet been ruled out (Clifton et al. 2008; Uzan et al. 2008; Biswas et al. 2010; Wang & Zhang 2012; Nadathur & Sarkar 2011). Zhang & Stebbins (2011) have excluded the Hubble bubble model as the possibility of cosmic acceleration using the the Compton- γ distortion. Zibin & Moss (2011) also concluded that a very large class of void models was ruled out using this method. Here we propose a powerful tool, the orientations of galaxy pairs to test the Copernican principle.

The Alcock-Paczynski (AP) test is a purely geometric test of the expansion of the Universe (Alcock & Paczynski 1979). Marinoni & Buzzi (2010) implemented the AP test with the distribution of orientations of galaxy pairs in orbit around each other in binary systems. The principle of this method is that the orientations is thought to be completely random, with all orientations being equally likely if measured assuming a cosmology that matches the true underlying cosmology of the Universe in a Friedmann-Lemaître-Robertson-Walker (FLRW) universe after the effect of peculiar motion is excluded.

In this paper, we implement the Alcock-Paczynski test with pairs of galaxies to test the Copernican principle. The void models cannot both fit SNe Ia plus CMB data and orientations of galaxy pairs. Our results exclude the possibility

^{*} fayinwang@nju.edu.cn

[†] dzg@nju.edu.cn

of the void models as the source of cosmic accelerating expansion and favor the Copernican principle.

2 THE VOID MODEL

We model the void as an isotropic, radially inhomogeneous universe described by the LTB metric,

$$ds^2 = -c^2 dt^2 + \frac{A^2(r, t)}{1 + k(r)} dr^2 + A^2(r, t) d\Omega^2, \quad (1)$$

where a prime denotes the partial derivative with respect to the coordinate distance r , and the curvature $k(r)$ is a free function representing the local curvature. The transverse expansion rate is defined as $H_\perp \equiv \dot{A}(r, t)/A(r, t)$ and the radial expansion rate is defined as $H_\parallel \equiv \dot{A}'(r, t)/A'(r, t)$, where an overdot denotes the partial derivative with respect to t .

The Friedmann equation in LTB metric is $H_\perp^2 = F(r)/A^3(r, t) + c^2 k(r)/A^2(r, t)$, where $F(r) > 0$ is a free function which determines the local energy density. The dimensionless density parameters can be determined as $\Omega_M(r)$ and $\Omega_K(r)$ by $F(r) = H_0^2(r) \Omega_M(r) A_0^3(r)$ and $c^2 k(r) = H_0^2(r) \Omega_K(r) A_0^2(r)$, where $H_0(r)$ and $A_0(r)$ are the values of $H_\perp(r, t)$ and $A(r, t)$ respectively at the present time $t = t_0$. So we can rewrite Friedmann equation in LTB metric as $H_\perp^2(r, t) = H_0^2(r) [\Omega_M(r) (A_0/A)^3 + \Omega_K(r) (A_0/A)^2]$. This equation can be integrated from the time of the Big Bang, $t_B = t_B(r)$, to yield the age of the universe at any given (r, t) ,

$$t_0 - t_B(r) = \frac{1}{H_0(r)} \int_0^{A/A_0} \frac{dx}{\sqrt{\Omega_M(r) x^{-1} + \Omega_K(r)}}. \quad (2)$$

The function, $A_0(r)$, corresponds to a gauge mode and we choose to set $A_0(r) = r$. As stressed by Silk (1977) and Zibin (2008), it is crucial to consider only voids with vanishing decaying mode, so we set $t_B(r) = 0$ everywhere. Although Biswas et al (2010) have shown that the void models were in better agreement with observations if the void has been generated sometime in the early universe. The null radial geodesics described by

$$\frac{dt}{dz} = -\frac{1}{(1+z)H_\parallel(z)}, \quad \frac{dr}{dz} = \frac{c\sqrt{1+k(r)}}{(1+z)A'(z)H_\parallel(z)}, \quad (3)$$

where $H_\parallel(z) = H_\parallel(r(z), t(z))$. The angular diameter distance and luminosity distance are given by

$$d_A(z) = A(r(z), t(z)), \quad d_L(z) = (1+z)^2 A(r(z), t(z)). \quad (4)$$

We will adopt the two parameterizations of the void profile $\Omega_M(r)$. The first one is the constrained GBH model (Garcia-Bellido & Haugboelle 2008)

$$\Omega_M(r) = \Omega_{M, \text{out}} + (\Omega_{M, \text{in}} - \Omega_{M, \text{out}}) \frac{1 - \tanh(r - r_0/2\Delta r)}{1 + \tanh(r_0/2\Delta r)}, \quad (5)$$

where the parameters r_0 and Δr characterize size and steepness of the density profile respectively. We wish to look only at voids that are asymptotically EdS, so we set $\Omega_{M, \text{out}} = 1$. We also set $\Delta r = 0.35r_0$, because this value can well fit the SNe Ia data (Garcia-Bellido & Haugboelle 2008; Marra & Paakkonen 2010). This density shape of GBH model can also explain other observations, such as CMB and BAO. The second one is a simple Gaussian form,

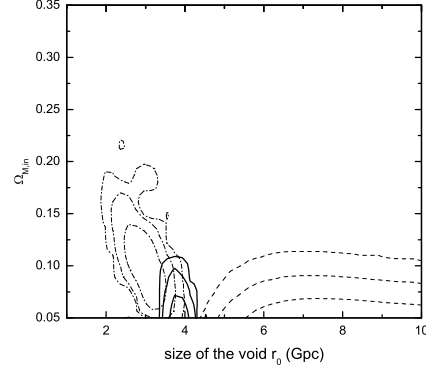


Figure 1. The 1σ , 2σ and 3σ contours in the parameter space $\Omega_{M, \text{in}} - r_0$ for the constrained GBH model. The dash-dot contours represent constraint from SNe Ia+CMB, the dashed contours from AAP, and the solid contours from SNe Ia+CMB+AAP. The best fit parameters are $r_0 = 3.0$ Gpc and $\Omega_{M, \text{in}} = 0.10$ for SNe Ia+CMB. But in order to fit the AAP, much more larger and underdense void are needed. This void model can not fit both the SNe Ia plus CMB data and the orientations of galaxy pairs.

$$\Omega_M(r) = \Omega_{M, \text{out}} + (\Omega_{M, \text{in}} - \Omega_{M, \text{out}}) \exp(-r^2/r_0^2), \quad (6)$$

where $\Omega_{M, \text{in}}$ and $\Omega_{M, \text{out}}$ are the matter density parameters at the observer's position and in the FLRW background outside the void, and r_0 characterizes the size of the void. It has been shown that this void profile can fit the observations of SNe Ia, CMB and BAO (Nadathur & Sarkar 2011).

3 CONSTRAINT FROM SNE IA, CMB AND PAIRS OF GALAXIES

We use the recent Union2 SNe Compilation (Amanullah et al. 2010), which consists 557 SNe Ia in the redshift range $z = 0.015 - 1.4$. With d_L in units of megaparsecs, the predicted distance modulus is $\mu(z) = 5 \log d_L(z) + 25$. The likelihood analysis is based on the χ^2 function:

$$\chi_{\text{SNe}}^2 = \sum_{i=1}^{557} \frac{[\mu(z_i) - \mu_{\text{obs}}(z_i) + \mu]^2}{\sigma_i^2}. \quad (7)$$

The parameter μ is an unknown offset. We marginalize the likelihood $\exp(-\chi_{\text{SNe}}^2/2)$ over μ , leading to a new marginalized χ^2 function:

$$\chi_{\text{SNe}}^2 = S_2 - \frac{S_1^2}{S_0}, \quad (8)$$

where $S_n = \sum_i [\mu(z_i) - \mu_{\text{obs}}(z_i)]^n / \sigma_i^2$.

We also use positions and amplitudes of peaks and troughs in the CMB spectrum to test the LTB models. The location of peaks and troughs can be calculated as Hu et al. (2001): $l_m = (m - \phi_m) l_A$, where $l_A = \pi \frac{d_A(z^*) (1+z^*)}{r_s^*}$, where $d_A(z^*)$ is the angular diameter distance with the sound horizon of r_s^* at the recombination redshift of z^* . We use the method of Marra & Paakkonen (2010) to calculate these values. We consider the position of the first, second, third

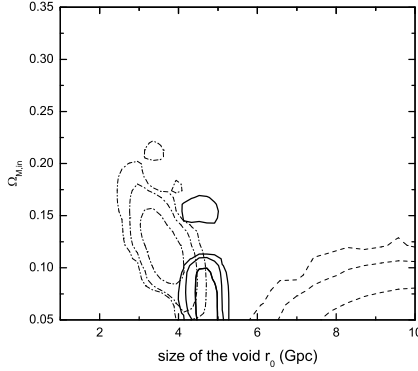


Figure 2. Same as Fig.2, but for the gaussian LTB model. The best fit parameters are $r_0 = 3.6$ Gpc and $\Omega_{M,in} = 0.12$ from SNe Ia+CMB. The AAP favors a much more larger and underdense void.

peak and of the first trough. We compute the corresponding phases ϕ_1 , $\phi_{1.5}$, ϕ_2 and ϕ_3 using the accurate analytical fits of Doran & Lilley (2002). The relative heights of second and third peak relative to the first one, H_2 and H_3 are also considered, for which we can use the fits of Hu et al. (2001). So the χ^2_{CMB} is (Marra & Paakkonen 2010)

$$\chi^2_{CMB} = \sum_{1,1.5,2,3} \frac{(l_m - l_{m,W7})^2}{\sigma_{l_m}^2} + \sum_{2,3} \frac{(H_j - H_{j,W7})^2}{\sigma_{H_j}^2}, \quad (9)$$

where the W7 represents the best-fit WMAP7 spectrum (Jarosik et al. 2011).

Pairs of galaxies should be distributed with random orientations if the fundamental assumptions of homogeneity and isotropy are correct. But two factors affect this simple cosmology test. First, peculiar velocities displace the position of a galaxy along the line of sight from its true position. Marinoni and Buzzi modelled the peculiar velocity distortion as a Doppler shift where the observed line of sight separation is related to the actual separation. Second, an observer needs to assume a cosmological model to convert observed angles and redshifts into comoving distances. The uniform distribution of orientations is distorted if a wrong underlying cosmology of the Universe is assumed.

In a non-flat Λ CDM universe, the tilting angle t subtended between galaxy pairs and the line of sight, can be written as

$$\sin^2 t = \{1 + [C_k(\chi_A) \cot \theta - \frac{S_k(\chi_A)C_k(\chi_B)}{S_k(\chi_B) \sin \theta}]^2\}^{-1}, \quad (10)$$

for details, see Marinoni et al. (2012). It is nontrivial to calculate the tilting angle and average anisotropy of pairs in LTB models. The measured galaxy (matter) clustering and its evolution agree with the standard Λ CDM cosmology to a factor of about 2 uncertainty up to $z \sim 1$ (Tegmark et al. 2004; Coil et al. 2006; Fu et al. 2008; Schrabback et al. 2010; Guzzo et al. 2008). A minimalist approach is to simply use the Λ CDM value since any viable LTB models must be consistent with these data. So we use the observed average anisotropy of pairs from Marinoni & Buzzi (2010) derived in Λ CDM cosmology. Zhang & Stebbins (2011) also

approximated the matter power spectrum by its form in a standard Λ CDM cosmology. The observed tilting angle is shifted to apparent angle τ because of the geometric distortions induced by the peculiar velocities of the pair's members. The probability distribution function of the apparent angle τ which is given by Marinoni & Buzzi (2010)

$$\Psi(\tau)d\tau = \frac{1}{2} \frac{(1 + \sigma^2)(1 + \tan^2 \tau)}{[1 + (1 + \sigma^2) \tan^2 \tau]^{3/2}} |\tan \tau| d\tau, \quad (11)$$

and the parameter σ depends on the cosmological expansion history as

$$\sigma(z) = \alpha \frac{H_0(r)(1+z)}{H_{||}(r,t)}. \quad (12)$$

The normalization parameter α is given by $\alpha = H_0^{-1} (\langle dv_{||}^2 / dr^2 \rangle)^{1/2}$. Because in the LTB metric, the transverse and radial expansion rates are different, so the correct value must be used in our calculations. When we use the galaxy pairs for AP test, the velocity perturbation σ used in equation (12) is related to the peculiar motions of the pair members along the line of sight. So we use radial expansion rate $H_{||}$ to calculate the velocity perturbation. Because the AP test is similar to BAO, we can see this formula is also similar to the redshift interval δz corresponding to the acoustic scale in the radial direction (Garcia-Bellido & Haugboelle 2008; Biswas et al. 2010; Marra & Paakkonen 2010). In the homogeneous Λ CDM model, Marinoni & Buzzi (2010) used the normal expansion rate $H(z)$. Marinoni & Buzzi (2010) derived the distribution $\Psi(\tau)$ as the average anisotropy of pair (AAP), which is given by

$$\mu_\sigma = \int \sin^2 \tau \Psi(\tau) d\tau = \frac{(1 + \sigma^2) \arctan(\sigma) - \sigma}{\sigma^3}. \quad (13)$$

At $z \approx 0$, Marinoni & Buzzi (2010) obtained $\alpha = 5.79_{-0.35}^{+0.32}$, using binaries in the seventh data release of the Sloan Digital Sky Survey (SDSS) (Abazajian et al. 2009). The normalization factor α is assumed to be constant for all redshifts and for different galaxy selections (Marinoni & Buzzi 2010). Although Jennings et al. (2012) found that the value of α could have a small variation with cosmology and redshift, Marinoni & Buzzi established that the changes of best fit value cannot exceed the 1σ confidence level if the variation of α is less than 10%. So this assumption could be reasonable. Belloso et al. (2012) also found that observations of close-pairs of galaxies do show promise for AP cosmological measurements, especially for low mass, isolated galaxies. The high-redshift (up to $z \approx 1.45$) AAP are obtained using the third data release of the DEEP2 survey (Davis et al. 2007). The value of χ^2_{AAP} is

$$\chi^2_{AAP} = \sum_{i=1}^9 \frac{[\mu_\sigma - \mu_{\sigma,obs}(z_i)]^2}{\sigma_{obs,i}^2}. \quad (14)$$

We adopt the value of $\mu_{\sigma,obs}$ and σ_{obs} from Fig. 2 of Marinoni & Buzzi (2010), which are shown as points in the Fig. 3. In order to verify the hypothesis that the normalization factor α is constant for all redshifts, the distance between the observed value of recession velocity difference square $\langle dV_o^2(z) \rangle$ and the prediction of equation (S20) in Marinoni & Buzzi (2010) is minimal (see Marinoni & Buzzi (2010) for more details). So this χ^2 value is

$$\chi_{\text{dV}^2}^2 = \sum_{i=1}^9 \frac{[\langle dV_o^2(z_i) \rangle - \langle dV^2(z_i) \rangle]^2}{\sigma_{dV_o^2, i}^2}. \quad (15)$$

We use the value of $\langle dV_o^2(z) \rangle$ and $\sigma_{dV_o^2}$ from Fig.(5S) of Marinoni & Buzzi (2010). The total χ_{AAP}^2 is

$$\chi_{\text{AAP}}^2 = \chi_{\text{AAP}}'^2 + \chi_{\text{dV}^2}^2. \quad (16)$$

In Fig. 1, we show the 1σ , 2σ and 3σ contours in the $\Omega_{M,\text{in}} - r_0$ plane for the constrained GBH model. In the calculation, the priors from WMAP7, such as the age of Universe $t_0 = 13.79$ Gyr and spectral index $n_s = 0.96$ are used (Komatsu, et. al. 2011). We also marginalize the Hubble constant H_0 in the range $50 \leq H_0 \leq 80 \text{ km s}^{-1} \text{Mpc}^{-1}$. The constraint from SNe Ia and CMB is shown as dash-dot contours, and dashed contours for AAP. The allowed range of r_0 is $1.80 \text{ Gpc} < r_0 < 4.10 \text{ Gpc}$ at 3σ level from SNe Ia+CMB. But the allowed range of r_0 is $r_0 > 4.42 \text{ Gpc}$ at 3σ level from AAP. These two contours do not overlap. So the constrained GBH model can not explain the observations of SNe Ia+CMB and AAP. The solid contours are derived from SNe Ia+CMB+AAP with $\chi_{\text{min}}^2 = 641.40$. While for the Λ CDM model, the minimum χ^2 is 620.37. The constrained GBH model is excluded at the 4σ confidence level compared to Λ CDM. In Fig.2, we show the 1σ , 2σ and 3σ contours in the $\Omega_{M,\text{in}} - r_0$ plane for the gaussian LTB model. The solid contours are derived from SNe Ia+CMB+AAP with $\chi_{\text{min}}^2 = 646.50$. This model is also excluded at the 4σ confidence level compared to Λ CDM. From the χ_{min}^2 of the two void models, we conclude that the precise form of the density profile may not be essential. Because the void models depend crucially on the void depth $\delta_\Omega = (\Omega_{M,\text{in}} - \Omega_{M,\text{out}})/\Omega_{M,\text{out}}$ and the void size r_0 . So our conclusion is almost independent of void model.

In Fig.3, we show the theoretical redshift scaling of the AAP in these two LTB models. In the up panel, we use the best fit parameters from SNe Ia+CMB for the constrained GBH model, $r_0 = 3.0 \text{ Gpc}$ and $\Omega_{M,\text{in}} = 0.10$. Obviously, the predicted values of AAP deviate from the observational values at high redshift. The χ^2 value is 37.35 for these nine data points. In the bottom panel, $r_0 = 3.6 \text{ Gpc}$ and $\Omega_{M,\text{in}} = 0.12$ are used for the Gaussian LTB model. The χ^2 value is 41.96 for these nine data points.

We must note that the local Hubble constant H_{loc} is also a big obstacle to the void models. Because the measurement of the Hubble constant is carried out mostly within a distance of roughly $r_{\text{loc}} \sim 200 \text{ Mpc}$ (Riess et al. 2011; Freedman et al. 2012), we obtain the H_{loc} (Marra & Paakkonen 2010)

$$H_{\text{loc}} = \int_0^{r_{\text{loc}}} H_0(r) 4\pi r^2 dr / (4\pi/3 r_{\text{loc}}^3). \quad (17)$$

In order to fit both the SNe Ia and CMB, the value of H_{loc} is $64 \pm 3.2 \text{ km s}^{-1} \text{Mpc}^{-1}$ in the constrained GBH model or $63 \pm 3.5 \text{ km s}^{-1} \text{Mpc}^{-1}$ in the Gaussian LTB model. Riess et al. (2011) determined the Hubble constant with 3% uncertainty as $73.8 \pm 2.4 \text{ km s}^{-1} \text{Mpc}^{-1}$. Freedman et al. (2012) measured the Hubble constant as $74.3 \pm 2.1 \text{ km s}^{-1} \text{Mpc}^{-1}$.

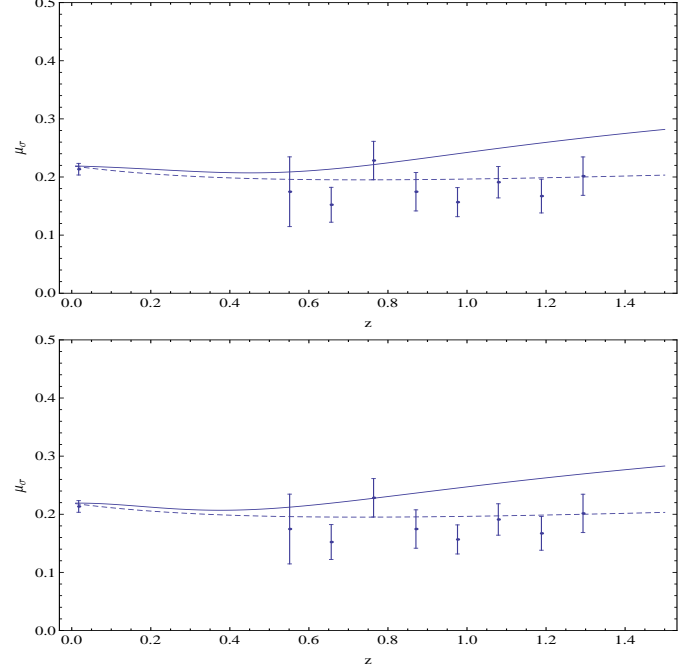


Figure 3. Points represent the observed average anisotropy of pairs. Solid lines represent the theoretical redshift scaling of the AAP as predicted by Eq. (13) in different LTB models with best fit parameters from SNe Ia+CMB, up panel for constrained GBH and bottom panel for gaussian LTB. The dashed line shows the best fit Λ CDM model with $\Omega_M = 0.25$ and $\Omega_\Lambda = 0.65$

4 DISCUSSIONS

Previous investigations show that void models can fit a variety of cosmological observations without containing dark energy because the lack of homogeneity gives a great degree of flexibility. For example, since the last scattering surface is far away from regions where SNe Ia are observed, the property of inhomogeneity allows a model to be constructed which provides different physical densities in the regions from which these two sets of observational data are drawn. So, the best way to constrain inhomogeneous models is using several sets of data that measure a range of observables at comparable redshifts. In this paper, we confront two general classes of void models with observations of SNe Ia, CMB and orientations of galaxy pairs. The redshifts of SNe Ia and orientations of galaxy pairs are almost in the same range. We find that these two void profiles *can not* fit both SNe Ia plus CMB data and orientations of galaxy pairs simultaneously. We also show that the two void models can fit both SNe Ia and CMB data, but at the expense of a Hubble constant so low that they can also be ruled out. So our results favor the Copernician principle. We must also note that our results are obtained under some assumptions, such as the chosen priors and void profile, which is also discussed in Biswas et al. (2010). So the void models are ruled out at the 4σ confidence level given the explored models and priors. But observations challenge the void models (Biswas et al. 2010; Zibin & Moss 2011). Future galaxy surveys such as BigBOSS (Schlegel et al. 2011) will provide improved precision of AAP function, placing much more strong constraints on inhomogeneity.

ACKNOWLEDGMENTS

We thank an anonymous referee for helpful comments and suggestions. We have benefited from reading the publicly available code of Marra & Paakkonen (2010). This work is supported by the National Natural Science Foundation of China (grants 11103007 and 11033002).

REFERENCES

- Abazajian K. N., et al., 2009, ApJS, 182, 543
 Alcock C., Paczyński B., 1979, Nature, 281, 358
 Alnes H., Amarzguoui M., 2006, PRD, 74, 103520
 Amanullah R., et al., 2010, ApJ, 716, 712
 Belloso A. B., et al., 2012, PRD, 86, 023530
 Biswas T., Notari A., Valkenburg W., 2010, JCAP, 11, 030
 Bondi H., 1947, MNRAS, 107, 410
 Bull P., Clifton T., 2012, PRD, 85, 103512
 Caldwell R. R., Stebbins A., 2008, PRL, 100, 191302
 Clarkson C., Bassett B., Lu T. H.-C., 2008, PRL, 101, 011301
 Clarkson C., Regis M., 2011, JCAP, 02, 013
 Clifton V. T., Ferreira P. G., Land K., 2008, PRL, 101, 131302
 Coil A. L., et al., 2006, ApJ, 644, 671
 Dai Z. G., Liang E. W., Xu D., 2004, ApJ, 612, L101
 Davis M., et al., 2007, ApJ, 660, 1
 Doran M., Lilley M., 2002, MNRAS, 330, 965
 Eisenstein D. J. et al., 2005, ApJ, 633, 560
 February S. et al., 2010, MNRAS, 405, 2231
 Freedman W. L. et al., 2012, ApJ, 758, 24
 Fu L. et al., 2008, A&A, 479, 9
 Garcia-Bellido J., Haugboelle T., 2008, JCAP, 04, 003
 Garcia-Bellido J., Haugboelle T., 2009, JCAP, 09, 028
 Goodman J., 1995, PRD, 52, 1821
 Guzzo L. et al., 2008, Nature, 451, 541
 Hu W., Fukugita M., Zaldarriaga M., Tegmark M., 2001, ApJ, 549, 669
 Jarosik N., et al., 2011, ApJS, 192, 14
 Jennings E., Baugh C. M., Pascoli S., 2012, MNRAS, 420, 1079
 Komatsu E. et al., 2011, ApJS, 192, 18
 Lemaître G., 1933, Ann. Soc. Sci. Brussels. A53, 51
 Marinoni C., Buzzi A., 2010, Nature, 468, 539
 Marinoni C., Bel J., Buzzi A., 2012, JCAP, 10, 036
 Marra V., Paakkonen M., 2010, JCAP, 12, 021
 Nadathur S., Sarkar S., 2011, PRD, 83, 063506
 Perlmutter S. et al., 1999, ApJ, 517, 565
 Riess A. et al., 1998, AJ, 116, 1009
 Riess A. G., et al., 2011, ApJ, 730, 119
 Schlegel D., et al., arXiv:1106.1706
 Schrabback T. et al., 2010, A&A, 516, A63
 Sherwin B. D., et al., 2011, PRL, 107, 021302
 Silk J., 1977, A&A, 59, 53
 Tegmark M., et al., 2004, ApJ, 606, 702
 Tolman R. C., 1934, PNAS, 20, 169
 Uzan J. P., Clarkson C., Ellis G. F. R., 2008, PRL, 100, 191303
 Wang F. Y., Dai Z. G., Zhu Z. H., 2007, ApJ, 667, 1
 Wang F. Y., Qi S., Dai Z. G., 2011, MNRAS, 415, 3423
 Wang H., Zhang T. J., 2012, ApJ, 748, 111
 Zhang P. J., Stebbins A., 2011, PRL, 107, 041301
 Zibin J. P., 2008, PRD, 78, 043504
 Zibin J. P., Moss A., 2011, Class. Quantum Grav., 28, 164005
 Zibin J. P., Moss A., Scott D., 2008, PRL, 101, 251303